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Could High H_{98} -factor Commercial Tokamak Power Plants use Nb-Ti Toroidal Field Coils?

S. B. L. Chislett-McDonald, E. Surrey and D.P. Hampshire

Abstract— In large engineering applications, materials that can fail by brittle fracture are avoided if there are practical, ductile alternatives. In recent years, advances in the experimental control and shaping of fusion energy plasmas have produced confinement times that are longer than the accepted IPB98(y,2) values (i.e. higher H_{98} -factors). Detailed understanding of these enhancements in H_{98} -factor is not available, but values as large as 1.5 - 1.8 may be possible [1, 2]. If such high values are reliably realized, they will enable such a large reduction in the magnetic field required from the toroidal field (TF) coils that ductile Nb-Ti becomes a possible superconducting materials choice for TF fusion energy magnets. In this paper we investigate what values of enhanced H_{98} -factor are required to enable the commercial use of Nb-Ti TF coils in tokamaks.

We have investigated the use of Nb-Ti TF coils in an ITER-like geometry, for a 500 MW net electricity producing tokamak using the PROCESS systems code [3, 4]. If we use present day Nb-Ti conductors, the minimum H_{98} -factor required for practical power plants is 1.5. For Nb-Ti cable with a critical current density increased by a factor of five, the minimum falls to $H_{98} \approx 1.4$. With this improvement for an $H_{98} = 1.5$, aspect ratio 3.1 (i.e. ITER-like geometry) tokamak, we find the cost of base-load electricity is $\sim 42\%$ greater than if Nb₃Sn is used and about 1.4 times that of a typical fission power strike price (scaled up to 2.5 GW_e net electricity).

Index Terms— Multifilamentary superconductors, Fusion reactor design, Toroidal magnetic fields, Type II superconductors

I. INTRODUCTION

ALTHOUGH Nb₃Sn is currently considered the best choice of superconducting material for the TF coils of the EU demonstrator reactor DEMO [5], its brittleness presents a significant challenge to reliable long-term operation. Improvements in the current sharing temperature and n -value of Nb₃Sn cables for the ITER TF coils and central solenoid, during electromagnetic and warm-up-cool-down cycling after 1/10th of the proposed number of cycles that the ITER TF coils will undergo, have been required [6]. Although their performance now meets the specification for ITER [7], residual concerns about the use of brittle Nb₃Sn are met by having one spare central solenoid coil and one spare TF coil [8]. Even so, replacing a damaged TF coil is considered a long time-scale and “high difficulty” event [9] that currently hinders commercialization of fusion energy. Rare-Earth-Ba-Cu-O (ReBCO) superconducting tapes are

being considered as an alternative to Nb₃Sn for applications in high-field, compact, fusion devices [1, 10] and are competing with the performance of low temperature superconducting cables [11]. However, they are also brittle and are currently much more expensive. Most commercial MRI machines use ductile Nb-Ti, despite the potential for cheaper, brittle, alternative superconductors being available. Choosing Nb-Ti mitigates against unforeseen risks such as manufacturing flaws and variability, that may lead to brittle failure. In developing our control and understanding of fusion plasmas, a number of unexpected events, including edge localized modes and disruptions such as vertical displacement events [12], were encountered. Although these phenomena are accounted for in ITER, the generation of fusion energy reactors after ITER will probably also produce more unexpected events. The magnet supports cannot be expected to withstand unforeseen phenomena which may then put the coils themselves at risk. Inevitably, commercial fusion tokamaks will try to avoid the use of brittle materials if at all possible. Nb-Ti based TF coils have not, to date, been considered viable for ITER or its successors, as they were considered unable to generate sufficiently high magnetic fields. However, the emergence of fusion devices with enhanced energy confinement times [1, 10] (and reduced field requirements) may make Nb-Ti a viable commercial alternative to its brittle competitors.

The energy confinement time of a tokamak is a key measure of device performance. Typically it is expressed in terms of the “ H_{98} -factor”: the ratio between the measured confinement time and that predicted from the IPB98(y,2) scaling [13]. ITER was designed using $H_{98} = 1.0$ [14] but ITER has considerable flexibility that means advanced plasma scenarios with plasma performance of $H_{98} \sim 1.57$ are now predicted in reversed shear operation [2]. $H_{98} \sim 1.8$ has also been suggested in the context of an “advanced tokamak” [1] justified by the large H_{98} -factors achieved in DIII-D [15]. Such high values were attributed to the presence of few low-order rotational q -surfaces, weak shear q -profiles and weak internal transport barriers. These advanced plasmas are inherently less susceptible to both magnetohydrodynamic instabilities (such as damaging edge localised modes) and the accumulation of impurities in the plasma core [2]. Ambitious values of $H_{98} = 1.9$ have been suggested for high-field

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spherical tokamaks [16, 17]. This value is based on the strong scaling of the confinement time with toroidal field observed in the spherical tokamaks, NSTX [18] and MAST [19]. However this strong confinement time scaling has also been attributed to plasma collisionality, rather than the toroidal field, and therefore may not be applicable to fusion power plants [20]. In summary, high H_{98} -factor fusion energy plants may be possible, but they are not yet proven.

In this paper, we identify new Nb-Ti TF coil designs that high H_{98} -factors (were they realizable) would make possible in a machine with an ITER-like aspect ratio 3.1, (we have not considered changing the superconductor of the central solenoid coil from Nb_3Sn). We present calculations of the cost of electricity (CoE) and the capital cost, when using Nb-Ti for the TF coils, for a 500 MW net electricity (MW_e), high H_{98} -factor tokamak power plant. We compare the CoE to other designs where the TF coils are built from Nb_3Sn and ReBCO. In all cases, we have optimized the design by minimizing the power plant capital cost. All calculations were undertaken using the PROCESS systems code [3, 4], developed at the Culham Centre for Fusion Energy. Details of uncertainty qualification in computational reactor design are given in [21].

II. FUSION POWER PLANT MODEL

A. Blanket and Shielding

The model for the reactor blanket was based on the helium cooled pebble bed, a design currently under investigation for use in EU DEMO [22]. The energy dissipation throughout the first wall, blanket and shield were calculated using parametric fits to a Monte Carlo N-particle neutron and photon transport model of a sector of a tokamak. We have made use of the same shielding model as was used in previous PROCESS simulations of EU DEMO A & B [3]. We have set the maximum allowable annual neutron fluence on the first wall to be 15 MW m^{-2} (equivalent to $\approx 2.1 \times 10^{26}$, 14.1 MeV neutrons). This is a far larger fluence than is expected at the TF and PF coils in ITER. In order to reach the magnets, the neutrons must pass through the first wall, blanket and vacuum vessel – where, the blanket will absorb the majority of the neutrons, maximizing both electricity and tritium production. As such, in this paper we have assumed that the neutron induced reduction in J_c is negligible. In intermetallic Nb_3Sn , fast neutron fluences up to $\approx 2 \times 10^{21}$ – $5 \times 10^{22} \text{ n m}^{-2}$ increase J_c because of increased resistivity and flux pinning.

At higher fluences the superconducting properties seriously degrade because of disorder [23, 24]. In oxide superconducting tapes, including REBCO, there is similar behavior [25]. In contrast, in the solid solution alloy Nb-Ti, although neutrons first degrade J_c , (J_c/J_{c0} reaches a plateau between 0.8 and 0.9 after a fluence of $\approx 3 \times 10^{22} \text{ n m}^{-2}$), the collapse of the superconducting properties at very high fluence has not been observed [23], and as such corresponding shielding requirements may not be so restrictive. It is still open, whether very high fluence tolerance can be added to ductility as another advantage of Nb-Ti.

B. Superconductor Model

The engineering critical current densities of the strands and tape, $J_{c,ENG}$, have been modelled using scaling laws. For Nb-Ti, we have used:

$$J_{c,ENG}^{Nb-Ti} = C_0(1 - b), \quad (1)$$

where $C_0 = 1.69 \times 10^9 \text{ A m}^{-2}$, $b = B/B_{c2}(4.22 \text{ K})$, $B_{c2}(4.22 \text{ K}) = 11 \text{ T}$. Values of $B_{c2}(4.22 \text{ K}) > 11 \text{ T}$ have been reported [26] and are not yet optimized in strands for fusion applications. For Nb_3Sn [27]

$$J_{c,ENG}^{Nb_3Sn} = \frac{C_1}{B} s(\epsilon)(1 - t^{1.52})(1 - t^2)b^{0.63}(1 - b)^{2.1}, \quad (2)$$

where $C_1 = 6.77 \times 10^9 \text{ A T m}^{-2}$, $t = T/T_c$, $b = B/B_{c2}(T)$. The strain dependent function $s(\epsilon)$ is given in [28]. The engineering critical current density of ReBCO tapes, $J_{c,ENG}$, was taken to be [27, 29-31]

$$J_{c,ENG}^{ReBCO} \approx \alpha(T) \left(1 - c(T) \cdot (\epsilon - \epsilon_0(T))^2\right) \cdot (1 - b) \exp\left(\frac{-B \cos \theta}{\beta_w(T)}\right). \quad (3)$$

where θ is the angle of the field with respect to the tape normal, and the functions $\alpha(T)$, $c(T)$, $\epsilon_0(T)$ and $\beta_w(T)$ are of the form

$$f(T) = U \left(1 - \frac{T}{T_c}\right)^V, \quad (4)$$

where T_c is taken to be strain independent and the values of U and V are taken from [27]. For Nb_3Sn strands and ReBCO tapes operating at 12 T and 4.22 K, $J_{c,ENG}^{Nb_3Sn} = 2.91 \times 10^8 \text{ A m}^{-2}$ and $J_{c,ENG}^{ReBCO} = 3.17 \times 10^8 \text{ A m}^{-2}$. For Nb-Ti strands operating at 6.4 T and 4.22 K, $J_{c,ENG}^{Nb-Ti} = 6.58 \times 10^8 \text{ A m}^{-2}$. These $J_{c,ENG}$ values are achieved in commercial conductors that typically have superconducting fractions of 34% for the Nb-Ti and Nb_3Sn strands and 1% for the ReBCO tapes. We have accounted for the presence of helium cooling channels, insulation and casing (which was allowed to vary) by reducing the cable critical current densities to $16 \pm 1\%$ of these values for Nb_3Sn and Nb-Ti and $39 \pm 2\%$ for ReBCO. In this work we have investigated how using superconducting cables with factor increases in $J_{c,Cable}$ affects the optimized tokamak design. We have used a notation where $J_{c,Cable} \times n$ corresponds to an increase in the cable critical current density by a factor n at all fields, temperatures and strains over current values. Such improvements can be achieved in the superconductor itself (recent calculations demonstrate J_c in superconductors is significantly below the theoretical limits [32]), improved architecture of the tapes or strands or improved design of the cable. For example, improvements in Nb-Ti can take advantage of the less demanding stability requirements for operating in the very high fields of a tokamak. The adiabatic transport current stability parameter for flux-jumping, β_T , [35, 36] is

$$\beta_T = \frac{\mu_0 \lambda^2 J_c^2 a^2}{C(T)(T_c - T)}, \quad (5)$$

where λ is the strand superconducting fraction, a is the filament diameter and $C(T)$ is the volumetric specific heat capacity. When β_T is smaller, the strand is more stable. Equation (5)

demonstrates that Nb-Ti strands bespoke for fusion, where J_c is relatively low compared to MRI applications, can have larger filament size a which will reduce strand production costs and/or have a higher superconducting fraction, λ , which will directly increase $J_{c,ENG}^{Nb-Ti}$. Improvements in ReBCO tapes can follow thicker or more superconducting layers, reduced substrate thickness, and or better artificial pinning centers in the ReBCO tapes [33, 34]. The temperature margin was set to 1.7 K for all superconductors in all magnet systems.

C. Costing

The capital costs and CoE were calculated assuming a 75% plant availability and a learning factor corresponding to a 10th of a kind fusion power plant (reducing cost by 0.65). Other studies have used factors between 0.5 and 0.8 [37]. Increased costs associated with high yield strength steels (for Nb₃Sn and ReBCO) were not accounted for. All costs presented are in 1990 US \$. The PROCESS costings module giving the costs of materials and manufacturing was calibrated in 1990 during the ITER Conceptual Design Activities [38]. Calculations of the price inflation and deflation of individual components and processes since then are beyond the scope of this paper. The costs used for the superconducting strands (and tapes) in the 1990 cost module were 6.1 \$/kA m for Nb₃Sn, 80.6 \$/kA m for ReBCO (at 12 T and 4.22 K) and 1.0 \$/kA m for Nb-Ti (at 6.4 T and 4.22 K) [27]. The costs were scaled using

$$\text{Cost}(B, T) = \text{Cost}(12 \text{ T}, 4.22 \text{ K}) \times \frac{J_{c,Cable}(12 \text{ T}, 4.22 \text{ K})}{J_{c,Cable}(B, T)}. \quad (6)$$

This scaling can be used to fold into the overall cost per \$/kA m, increases in $J_{c,Cable}$ and increases in manufacturing costs. An increase in critical current density of the cable by a factor of n , without increased manufacturing cost, leads to a corresponding decrease in \$/kA m by a factor of n . PROCESS assumes the same types of magnet structure (casing, winding etc.) for different superconductors and scales their sizes for the purposes of costing [3, 4].

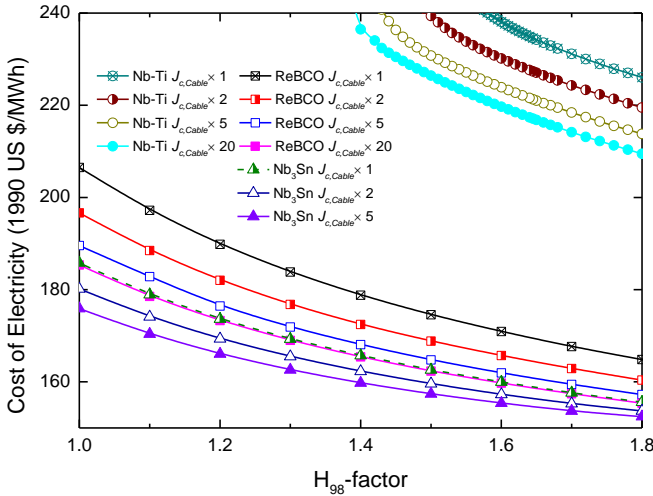


Fig. 1. The Cost of electricity (CoE) in 1990 US \$/MWh as a function of H_{98} -factor for a 500 MW_e, aspect ratio 3.1 fusion power plant. ReBCO, Nb₃Sn and Nb-Ti toroidal field coils are considered, where $J_{c,Cable} \times 2$ refers to a critical current density of a cable twice that for cables using current strands.

TABLE I
COMPARISON BETWEEN THE DESIGN OF THREE 500 MW NET ELECTRICITY, H_{98} -FACTOR = 1.5, ASPECT RATIO 3.1 TOKAMAKS WITH DIFFERENT TF COIL SUPERCONDUCTORS

	Nb ₃ Sn	ReBCO ($J_{c,Cable} \times 5$)	Nb-Ti ($J_{c,Cable} \times 5$)
Fusion Power (GW)	2.05	2.05	2.09
Plasma β (%)	5.33	5.32	5.22
Major Radius (m)	6.74	6.81	9.28
Peak Field (T)	12.7	13.0	10.1
Steel Op. Stress (2/3 Y.S.) (MPa)	667	667	667
Field on axis (T)	5.90	5.78	4.68
Plasma current (MA)	16.1	16.0	17.6
Capital Cost (bn\$)	4.06	4.14	6.51
CoE (\$/MW h)	163	165	231

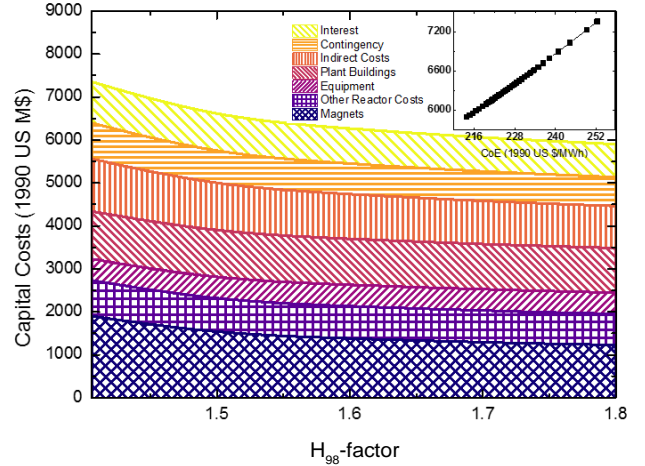


Fig. 2. Capital costs (in million 1990 US \$) as a function of H_{98} -factor for a 500 MW_e, aspect ratio 3.1 fusion power plant where Nb-Ti with a five-fold increase in its critical current density has been used for the toroidal field coils. Inset: Capital costs (in million 1990 US \$) vs the cost of electricity (in 1990 \$/MWh) of a 500 MW_e, aspect ratio 3.1 fusion power plant where Nb-Ti $J_{c,Cable} \times 5$.

III. RESULTS AND DISCUSSION

A. Minimum H_{98} -factor for Nb-Ti use

Fig. 1 displays an optimized CoE of a 500 MW_e, aspect ratio 3.1 fusion power plant as a function of H_{98} -factor obtained by minimizing the capital costs of the plant. We find that it becomes practical to use Nb-Ti for the TF coils, only for H_{98} -factor values above ~ 1.4 . We have calculated the CoE for a power plant with Nb-Ti TF coils with $J_{c,Cable} \times 5$ and $H_{98} = 1.5$. The CoE is $\sim 42\%$ greater than an equivalent power plant with Nb₃Sn TF coils. For $J_{c,Cable} \times 2$, this increases to $\approx 47\%$.

A comparison between three, 500 MW_e, aspect ratio 3.1, $H_{98} = 1.5$ tokamaks with Nb₃Sn, ReBCO ($J_{c,Cable} \times 5$) and Nb-Ti ($J_{c,Cable} \times 5$) is shown in Table I. The CoE of an $H_{98} = 1.5$, Nb-Ti reactor is ≈ 3.5 times greater than that of the very large nuclear fission plants, such as the Hinkley Point C reactor in the UK (with inflation considered) [39]. However, assuming the tokamak power plant CoE scaling with net electricity (i.e. size) in [27] is applicable to Nb-Ti, we find that a similarly designed 2.5 GW fusion reactor would have a CoE only $\sim 40\%$ greater. Converting the current CoE of solar and wind power [40] to 1990 US \$ yields, for these intermittent sources, ~ 60 \$/MWh and ~ 25 \$/MWh respectively.

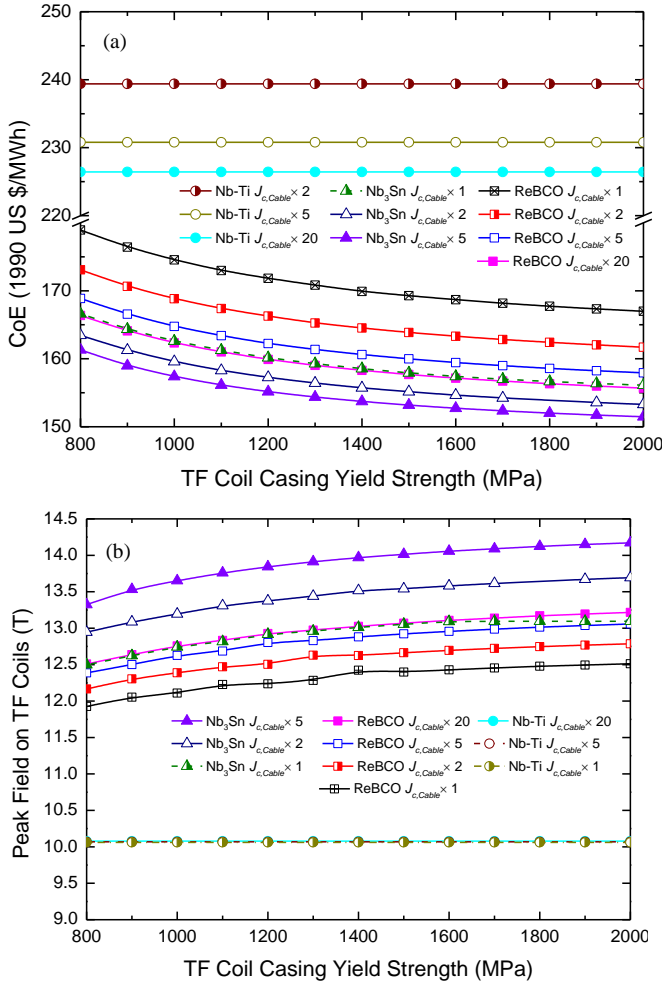


Fig. 3. (a) The cost of electricity in 1990 US \$/MWh and (b) The peak field on the TF coils of a 500 MW_e, aspect ratio 3.1 fusion power plant as a function of the yield strength of the TF coil casing. Results are plotted for ReBCO, Nb₃Sn and Nb-Ti toroidal field coils, where $J_{c,Cable} \times 2$ refers to a cable critical current density twice that using present strands.

B. Capital Cost of an Nb-Ti Based Reactor

Fig. 2 shows a breakdown of the capital costs of a 500 MW_e, aspect ratio 3.1, where Nb-Ti with $J_{c,Cable} \times 5$. The magnets account for $\sim 60\%$ of the reactor costs and $\approx 20\%$ (for $H_{98} = 1.8$) to $\approx 22\%$ (for $H_{98} = 1.5$) of the total plant capital costs. The total capital costs range from 7.4 bn\$ at $H_{98} \approx 1.4$, to 5.9 bn\$ at $H_{98} = 1.8$. The inset of Fig. 2 shows that minimising the capital cost is equivalent to minimising the cost of electricity.

C. TF Coil Casing Yield Strength Effect on CoE

The results from our investigation into the effects of increasing the TF coil casing yield strength are shown in Fig. 3. We have limited peak stress to $2/3$ of the yield stress of the steel. A description of the PROCESS coil casing stress model is given in [41]. An increased casing yield strength enables a stronger field in the cases of ReBCO and Nb₃Sn cables. This in-turn leads to a reduction in the plasma volume required to generate 500 MW_e (as $P_{fus} \propto B_T^4 R^3$) and device major radius. A smaller device results in a lower capital cost and a corresponding lower cost of electricity. These considerations together with Carnot

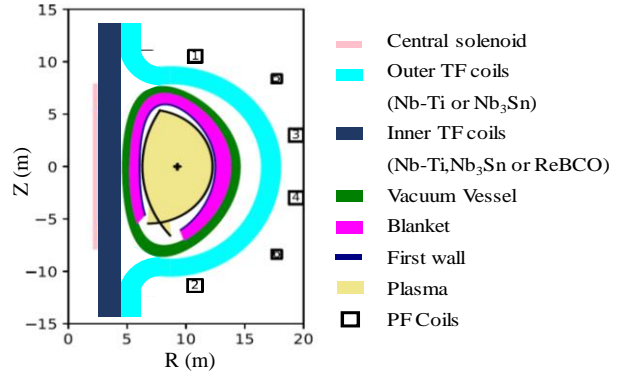


Fig. 4. Height from the plane of symmetry vs radial distance from the axis of symmetry of a 500 MW_e, $A = 3.1$ fusion reactor with Nb-Ti ($J_{c,Cable} \times 5$). The TF coils are of the demountable Durham/CCFE “half-Phi” design.

efficiency considerations, related to the efficiency of converting heat into electricity, have led to a drive towards developing advanced stronger steels that operate at higher temperatures.

Advanced steels are not necessary for Nb-Ti tokamaks as shown in Fig. 3. The optimal field is limited by $J_{c,Cable}$ of Nb-Ti at fields close to its upper critical field. Steels with yield strengths of 1000 MPa, or lower, and perhaps operating at higher temperatures, are able to withstand the stresses at the magnetic fields produced using Nb-Ti. The reduction in CoE as a result of using higher $J_{c,Cable}$ only really affects the cost, not the size/geometry of the tokamak.

IV. FUTURE PROSPECTS

The high ductility and stability of Nb-Ti make the use of demountable magnets and remote handling more straightforward than for brittle materials [42]. Such joints would offer significant improvements in the availability of a reactor, from the 75% assumed in this work, by improving the ease of replacing coils. They would also enable modular construction, likely decreasing capital costs [43]. Novel designs of the TF coils are also expected to drive costs down. Fig. 4 shows a reactor with demountable jointed TF coils (based on the Durham/CCFE “half-phi” design [42]) that considers the topology/availability of the tokamak, the location of the joints and the use of different superconductors.

V. CONCLUSIONS

Our calculations show one can build a net electricity producing fusion device with Nb-Ti, if the H_{98} -factor of the device is sufficiently high. The minimum is H_{98} is ≈ 1.5 for present Nb-Ti strands and ≈ 1.4 with for improvements to $J_{c,Cable} \times 5$. We have found that for a 500 MW_e, aspect ratio 3.1, $H_{98} = 1.5$ tokamak power plant (optimized to minimize its capital cost), using Nb-Ti with $J_{c,Cable} \times 5$ for the TF coils, results in a CoE $\approx 42\%$ greater and a capital cost $\approx 60\%$ greater than a device where Nb₃Sn is used. These differences increase to $\approx 47\%$ and $\approx 68\%$, respectively, when using Nb-Ti with $J_{c,Cable} \times 2$. The majority of these increased costs are due to the greater plasma volume required to generate 500 MW_e at the lower field produced by Nb-Ti magnets. Additional costs from the large TF

coils offset the reduced cost of Nb-Ti. The value of plant availability assumed here of 75% is very conservative. Magnets of ductile Nb-Ti will be more resilient to future unforeseen plasma phenomena than magnets made from brittle Nb₃Sn or ReBCO. There is no need for advanced steels if Nb-Ti is used for the TF coils since a yield strength of 800 MPa is sufficient to withstand the forces generated in the relatively low-field Nb-Ti TF coils.

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